Environmental Engineering and Management Journal

May 2020, Vol. 19, No. 5, 747-753
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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EFFICIENCY INDICATOR FOR ASSESSMENT OF WATER DISTRIBUTION NETWORKS CARRYING CAPACITY

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Abstract

A water distribution network's (WDN's) flow capacity decreases over time mainly because of the unplanned demand growth at its consumption points, increased water loss, and increased internal roughness caused by aging of pipes. In this context, this work presents a new performance indicator, the Carrying Capacity Indicator (I_{CC}). It will enable utility managers to evaluate WDNs' hydraulic and energy efficiency. The I_{CC} was applied in a real case study: a sector of the João Pessoa WDN, in Brazil. Considering only design criteria (in relation to nodal demands and pipe roughness), the I_{CC} decreased from 203.5% in the first year of the network's operation to 70.6% in its 30th year of operation. Simulation results are provided to demonstrate that the proposed indicator can be successfully applied to a wider class of WDNs.

Key words: hydraulic efficiency, performance indicators, water supply networks

Received: February, 2019; Revised final: August, 2019; Accepted: November, 2019; Published in final edited form: May 2020

1. Introduction

The main function of a water distribution network (WDN) is to provide users water in compliance with quality and service standards under various conditions. The ability to meet the water demand at the nodes at the required pressures depends on many characteristics of the network, such as various infrastructural components (Maiolo et al., 2018). Generally, a WDN can be defined as a complex system consisting of numerous structural elements, whose function is to provide the final consumer water for domestic, industrial, and public-consumption purposes.

WDNs' flow capacity often decreases over time mainly because of the unplanned demand growth at the consumption points, increased water loss, and increased internal roughness caused by aging of pipes. In this context, the development of indicators for the assessment of WDNs' hydraulic and energetic conditions is imperative. Indicators should provide water utility information for the monitoring of the system's efficiency and comparison with other WDNs and to promote benchmarking. Due to the WDN's intrinsic complexity and the variety of parameters that influence the pipes' carrying capacity, determining the hydraulic and energy efficiency is still quite a complex process. A well-designed indicator should interpret the system-specific characteristics and allow for the evaluation of efficiency in an easy and understandable way.

Considering the importance of the development of methods to analyze WDNs' efficiency, the present work expands the technical-scientific knowledge of the application of the performance indicators for the efficiency of water

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mains. These indicators should allow for the comparison between a WDN's actual situation and its optimum operational condition (which, in general, corresponds to the integral system-design situation), represented by a reference value.

Considering the above, the following problem question is presented to guide the present study: How can we evaluate WDNs' hydraulic and energy efficiency, a crucial element for urban water supply? In response to this question, the research objective was to develop a performance indicator to analyze WDNs' efficiency in relation to their carrying capacity.

2. Literature review

When describing WDNs' efficiency, the literature generally refers to indices directly related to the pumping systems' electrical energy consumption. Measuring pump stations' electrical efficiency is a more intuitive process than measuring water mains' hydraulic and energy efficiency. Papa et al. (2014) evaluated the electrical efficiency of 152 pump systems in Ontario (Canada). This study's results indicated the water supply-system pumps in Ontario typically operate at 73.7% efficiency.

A few researchers have attempted to design performance indicators that combine a WDN's mechanical energy efficiency with the electro-mechanical pump efficiency. The most commonly used energy indicator to determine the pump system's energy efficiency is the specific energy consumption (SEC), which is the ratio between the total energy the pumps consume and the volume of water entering the system. The SEC is a valid energy intensity measure for the analysis of an isolated WDN but does not account for unique system characteristics that have a significant effect on energy consumption, such as topography, leakage, friction losses, and demands. To compare WDNs, the International Water Association (IWA) developed the normalized SEC. The term "normalized" refers to the calculation of the SEC for the same standard head, 100 m in this case, which allows for the comparison of WDNs.

Pelli and Hitz (2000) proposed an indicator to evaluate energy, which was defined as the ratio between the actual consumed energy and the minimum theoretical energy, taken as the energy level of comparison. This minimum energy term normalized a system's unique demand and pressure requirements, allowing for a more accurate comparison of WDNs' energy efficiencies. However, the minimum energy term did not incorporate two major energy losses, unavoidable energy losses due to friction and leakage.

Based on the indicators Pelli and Hitz (2000) developed, Cabrera et al. (2010) developed five energy indicators to describe the excess of supplied energy, network energy efficiency, energy dissipated through friction, leakage energy, and standards compliance in WDNs. Gay and Sinha (2011) incorporated unavoidable energy losses due to friction and leakage into Pelli and Hitz's (2000) minimum-energy term. The researchers developed an indicator that evaluates the energy efficiency of water transport by comparing the current energy use (including the electrical energy use of pump systems) to the minimum energy. Because the energy entering the distribution system includes the pumps' electrical-energy use, the minimum-energy term also includes a maximum pump-efficiency value. This indicator does not allow for complete identification of energy inefficiencies caused by losses and avoidable leaks.

Lenzi et al. (2013), relying on Cabrera et al. (2010), developed the WSEE (water supply energy efficiency) indicator, which breaks down a WDN's energy efficiency into three main components: network energy efficiency, leakage energy efficiency, and pumping energy efficiency. The first is similar to Pelli and Hitz's (2000) indicator, comparing the energy use to the minimum energy required by the users. To obtain the entire WDN's energy efficiency, the three terms are multiplied together.

Cabrera et al. (2014) presented three new indicators to assess a WDN's energy efficiency. The first two indicators represent the ideal energy consumption (minimum energy required by system) and the actual energy consumed. The third indicator provides an achievable goal linked to inefficiencies in the system (e.g., pump systems, leakage, and friction loss). This approach was the first to quantify all major unavoidable energy losses in a WDN. By applying the energy indicators described, Cabrera et al. (2014) found topography and layout are two key drivers of energy use in WDNs and pressurized irrigation systems. In practice, calculating these indicators in complex looped networks and various pipe diameters is difficult because it is necessary to estimate the average path length and the overall unit head loss across an entire system. This fact could be a substantial barrier preventing utility managers from adopting these indicators.

Recently, researchers have focused on developing energy indicators to assess the energy implications of the operation of distribution systems (Scanlan and Filion, 2017). Prosser et al. (2014) conducted a sensitivity analysis to examine the influence of factors such as leakage volume, leakage duration, pipe break rate, and pump efficiency on energy use in WDNs in the Midwest (USA). The indicator Dziedzic and Karney (2015a) developed maps the mechanical energy flow geographically and temporally in a WDN. Hashemi et al. (2015) introduced new pipe-level energy metrics to evaluate the energy transformations in a WDN's individual pipes. To evaluate these metrics, the energy supplied to each pipe is categorized as delivered and required energy, leakage, friction, and surplus energy, which are then compared to each other. This method quantifies all major energy losses for a pipe segment through a pipe-level energy balance. This energy balance is then calculated hourly for all the system's pipes. The researchers also showed that certain pipes' energy profiles differ depending on their location in the network and the time of the day.

Snider (2017) developed a streamlined method to assess a WDN's energy efficiency without the need for hydraulic modeling or extended simulation. This indicator compares the current energy supplied to a distribution system to its theoretical minimum energy requirement (considering unavoidable energy losses due to friction, leakage, and user demand). Mamade et al. (2017) also presented a method to assess an entire WDN's energy efficiency without a hydraulic model or extended simulation by simply dividing the minimum energy required by the end-users by the total energy entering the system (including the electrical energy the pumps consume). Scanlan and Filion (2017) applied previously developed energy indicators to evaluate and compare the energy efficiency, energy lost to friction, energy lost to leakage, and surplus energy in four systems in Ontario (Canada). The results show that the systems had a high energy efficiency ranging from 75-94% (leak-free) and 58-70% (leaky).

It is important to highlight that the energy indicators previously developed for WDNs do not provide a methodology that accounts for the influence of the carrying-capacity deterioration and the unplanned growth of the demand in the specific evaluation of water mains' efficiency. Unpredicted expansions, verticalization of non-predicted buildings, increased internal roughness due to the aging of pipes, and increased water loss are issues that lead to the deterioration of the pipes' capacity and cannot be neglected in the development of indicators for WDNs.

With the advent of hydraulic models and extended simulations, a more detailed analysis of energy efficiencies became possible. Hydraulic models allowed researchers to develop energy indicators that map energy flows throughout the distribution system at specific steps. This development eliminated the error associated with system-wide averaging of characteristics (such as elevation and pressure), which is necessary for energy indicators that do not require a hydraulic model. Therefore, the energy indicators that require a hydraulic model provide greater detail and insight into a WDN's mechanical-energy efficiency (Snider, 2017).

The literature registers the lack of efficiency indicators in the analysis of WDNs because most of the indicators address these systems' energy situations (Vilanova and Balestieri, 2015). This research is original for two reasons. First, previous research has focused on quantifying the energy based on the consumption of pumping systems. With this research, we sought to understand the current state of energy efficiency indicators for WDNs and design a mechanical indicator to evaluate the water mains' carrying capacity.

Water utilities will be able to use the indicator developed in this paper as a screening-level tool to identify performance issues and improve the choice of most promising solutions regarding energy and hydraulic efficiency. Second, previous research in energy-indicator use has mostly concerned European WDNs (e.g., Lenzi et al., 2013; Mamade et al., 2017), North American systems (e.g., Gay and Sinha, 2010; Prosser et al., 2014), and Canadian systems (e.g., Dziedzic and Karney, 2015b; Scanlan and Filion, 2017). The current study is one of the first examinations of the aforementioned system-energy relationships in a South American system.

3. Material and methods

3.1. Case study

The proposed method was applied in a real WDN in the metropolitan region of João Pessoa (Fig. 1), which is the main city in the state of Paraíba, Brazil, with a population of over 800 thousand inhabitants. It is also an important educational, industrial, and technological center of Northeastern Brazil. The case study discussed is the Bessa network, which is made up of PVC pipes with diameters ranging from 50 to 600 mm.

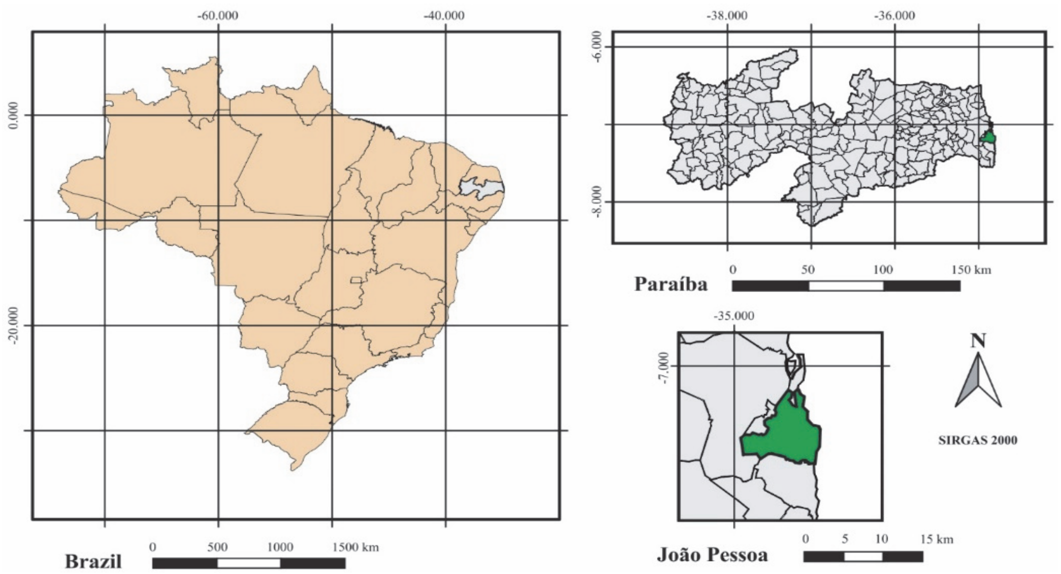

Fig. 1. Location of the case study on the map of Brazil

The following are this network's specifications:

- length of pipe: 134 km.
- number of pipes: 1580.
- number of junctions: 1387.
- the network's year of implementation: 2003, with a design period of 20 years.

All hydraulic analyses of the Bessa network were performed in the hydraulic model developed with the EPANET software (Fig. 2). The hydraulic model's nodes and system parameters were calibrated with field data. The system model's hydraulic outputs (flow in pipes, pressure and flow at nodes, output pressure, input flows, and levels and volumes in storage tanks) were used to calculate the indicator values in each scenario.

3.2. Carrying Capacity Indicator (I_{CC})

The carrying capacity is related to this network's ability to satisfy the demands imposed on its nodes. A flow capacity of the systems decreases over time mainly due to the unforeseen growth in consumption, the high water losses, and increased friction losses caused by aging of pipes. The I_{CC} is measured by comparing the efficiency of the evaluated scenario and a reference scenario. Fig. 3 shows the flowchart of the proposed methodology.

The indicator used to evaluate each of the scenarios is called energy dissipated by the network (I_{ED}). This indicator is calculated by dividing the energy lost through friction along a system's pipes by their total length. The energy lost through friction can be calculated using the sections' hydraulic characteristics (application of traditional head-loss formulas, such as that proposed by Darcy-Weisbach and Hazen-Williams) or the decay of the piezometric head in each pipe. Therefore, the I_{ED} can be calculated according to (Eq. 1):

$$I_{ED} = \frac{\sum_{i=1}^{N}(H_{1i} - H_{2i})}{L} \tag{1}$$

where: I_{ED} is the energy dissipated in the network, H_1i is the piezometric head at a node upstream from stretch i, H_2i is the piezometric head at a node downstream from stretch i, i is the number of the pipe, N is the number of pipes in the network, and L is the total length of pipe.

The I_{CC} is the ratio between the energy dissipated in the network, corresponding with the predicted scenario in the original design (with the predicted demands and expected roughness), $I_{ED}\ ref$, and the situation corresponding to the effectively evaluated scenario at a given time (whether before or after the design period that was originally conceived), $I_{ED}\ eval$. The I_{CC} is calculated as follows (Eq. 2):

$$I_{CC} = \frac{I_{ED}\ ref}{I_{ED}\ eval} \times 100 \tag{2}$$

A 100% value for the I_{CC} indicates that the analyzed network is in sound operational condition regarding its water flow capacity when compared to the standard scenario. Values above 100% indicate that the network is operating under more favorable conditions then the operation conditions provided in the original design. Conversely, values less than 100% indicate that the network is hydraulically inefficient because it is consuming more energy with losses than was initially predicted in the baseline scenario. As a consequence, in this last case, the available effective pressures at the network nodes are under the pre-established values in the design, decreasing the quality of the supply service. Therefore, it is possible to evaluate a system in a given scenario or to estimate the behavior of its efficiency over time, thereby obtaining conclusions on the possible network rehabilitation that are needed.

Fig. 2. Bessa network in EPANET

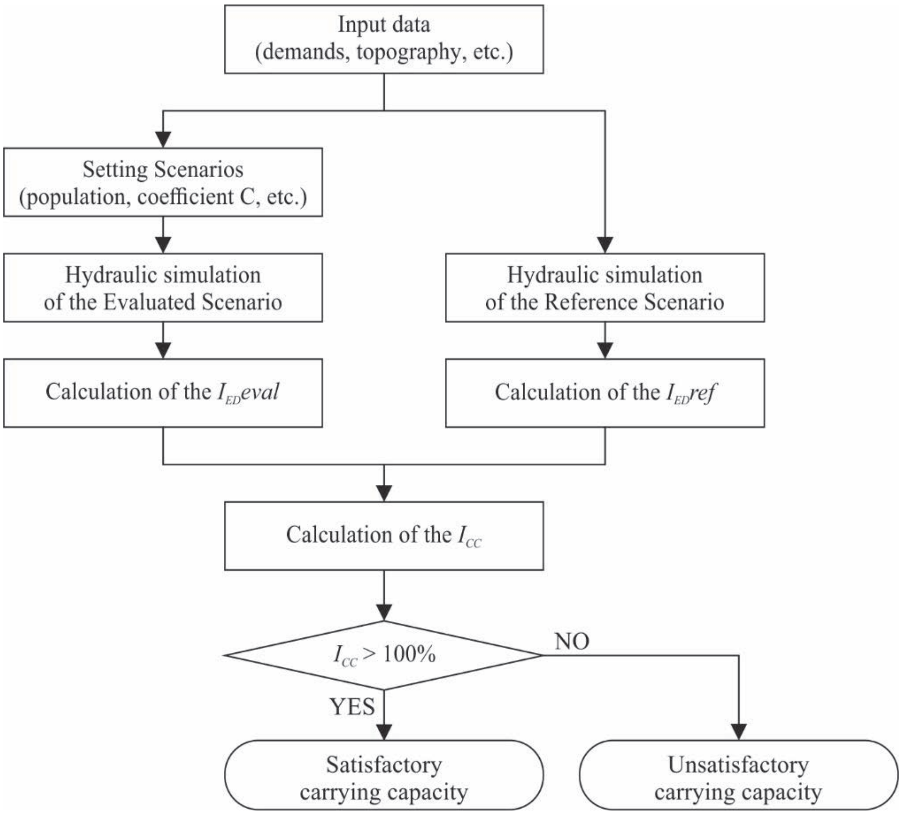

Fig. 3. Flowchart of the methodology

The efficiency decrease in a hydraulic network over time can be caused by the unplanned growth in user demand consumption, increased water loss, and/or incremental head loss in the pipes due to their increased roughness.

4. Results and discussion

To calculate the Bessa network's I_{CC} values in several scenarios, it was necessary to calculate the demands on the nodes and the pipes' roughness in the network model that simulates increasing water demands on the network nodes over time.

In the first situation, the operation of the Bessa network was hydraulically simulated considering the original project's population growth rate. Based on the simulation for the Bessa network's initial operation year, the evolution values of the I_{CC} were determined over time. These simulations were performed from year 1 of operation to year 30 (2032), changing every five years. Therefore, the network's operating conditions altered every five years, changing the water demands on the nodes and the pipes' roughness in each scenario. The pipes' roughness varied according to the data recommended by the specialized bibliography of Brazil (e.g., Azevedo Netto and Fernández, 2015). Considering that the Bessa network pipes are PVC, the Hazen-Williams roughness coefficient, C, ranged from 140 (2003) to 125 (2022). A variation of 2.5 units of the coefficient was estimated for every 5 years of network operation.

The network's increase in water demand was set at a rate of 1.55% per year. Knowing the population in each scenario made it possible to obtain factors that would be multiplied by the demands in the first year of operation to estimate the future demands in each scenario. These factors were calculated as the simple ratio between the population of the scenario and the population at year 1 of the network's operation. Table 1 shows estimated population, the network's total flow, and the results obtained from the I_{CC} calculation. As expected, the network only becomes hydraulically inefficient (i.e., the I_{CC} drops below 100%), requiring possible rehabilitation actions, after 20 years of operation, which corresponds to the design period.

The second evaluation included an annual rate of 6.18% for population growth and water demand, which was determined from the real data measured in the field. Fig. 4 shows the results of the hydraulic simulations with the original design's data and with parameters measured in the field for 2013, when the simulated network with real data was already inefficient. Fig. 4b highlights areas that have nodes with unsatisfactory pressures (values below 10 m). The results confirm the real conditions because the construction of high residential properties in these areas resulted in population growth the designer did not predict. To determine the year of operation in which the network became inefficient, the I_{CC} was calculated annually for the years (inclusive) between 2008 and 2013. The results are presented in Table 2, which shows that the network becomes inefficient in early 2009. When real analyses were incorporated (especially in relation to the demographic growth verified by the network-supplied district), the network became inefficient within six years of operation. The results of the I_{CC} contribute to the conditions water utility technicians reported in interviews. They pointed out that the problem concerning the low pressures in the network began in 2009. Consequently, we can see that the results are quite consistent when compared to the actual supply.

Table 1. I_{CC} for the Bessa network regarding the design criteria

Year	2003	2008	2013	2018	2023	2028	2033
Population	26237	28334	30600	33045	35687	38540	41621
Total flow (L/s)	216.92	234.26	252.99	273.21	295.05	318.64	344.11
I_{ED} eval (m/km)	2.10	2.53	3.07	3.62	4.27	5.10	6.05
I_{CC} (%)	203.50	168.91	139.05	117.84	100.00	83.68	70.55

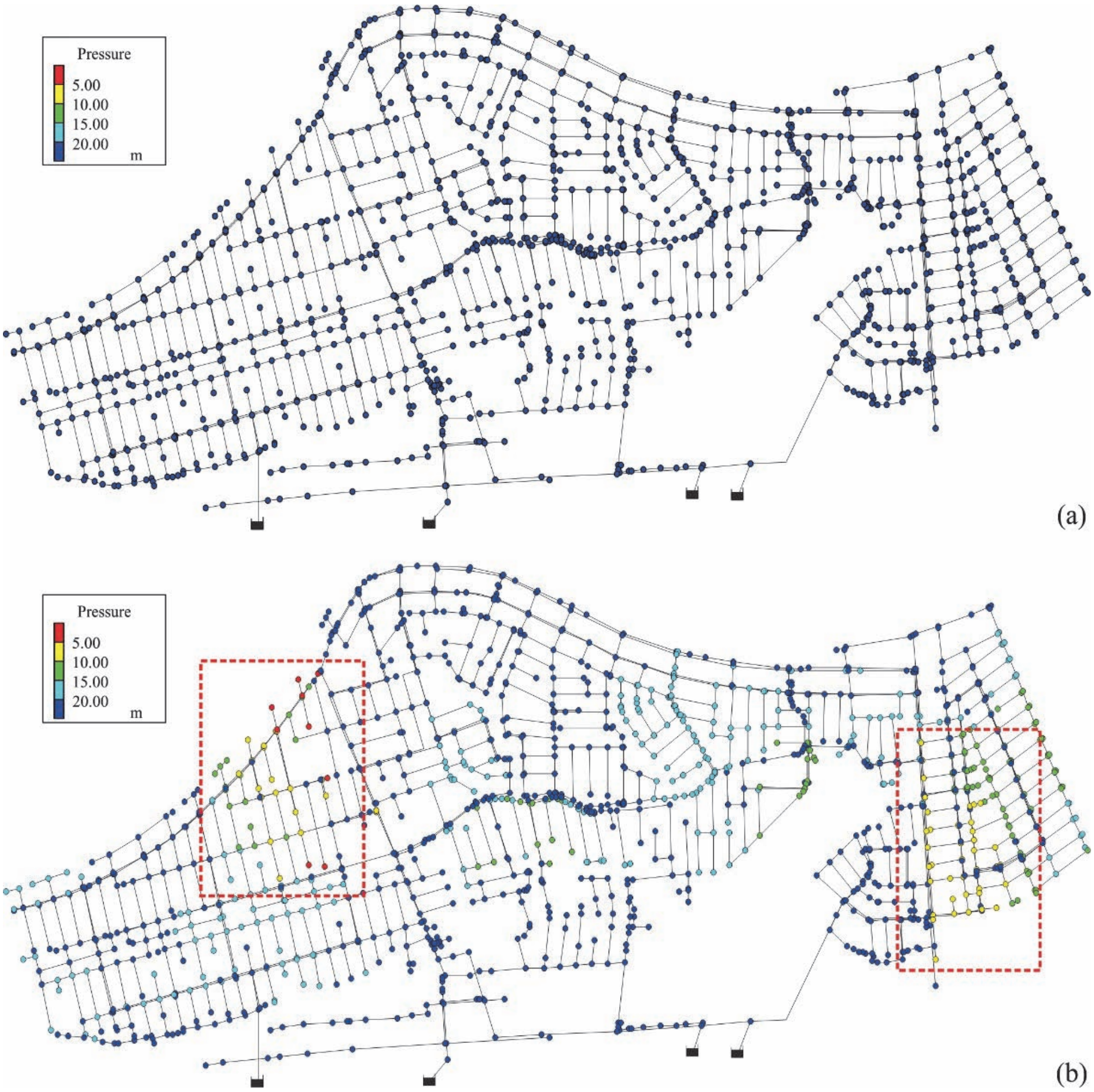

Fig. 4. Pressures in the Bessa network in 2013, (a) original design criteria, (b) simulation with parameters measured in the field

Table 2. Generated results to measure the actual moment of inefficiency in the Bessa network

Year		2008	2009	2010	2011	2012	2013
Population		35402	37588	39909	42373	44990	47768
Total flow (L/s)		294.03	312.17	330.75	350.84	371.51	394.64
I_{CC} (%)	***Design***	4.27					
	Actual	4.06	4.54	5.06	5.63	6.28	7.02
I_{ED} eval (m/km)		105.06	94.01	84.43	75.84	67.95	60.79

It is worth mentioning that it is possible to apply the proposed method in cities around the world because the indicator only requires physical characteristics of the water main and demand data. Because the indicator is described as a percentage, the comparison between WDNs can be performed satisfactorily, provided that the reference scenario is fixed. The methodology's main limitation is in the difficulty of obtaining the network data and calibrating the hydraulic model.

5. Conclusions

The Carrying Capacity Indicator (I_{CC}) presented in this study quantifies, for all networks, the relationship between the energy dissipated through head loss in a reference scenario (e.g., the original network design) and the analyzed scenario. The evaluation scenario has its index calculated within the network's operational limits at a specific time, considering the demand variation and/or change in the pipe's roughness. The indicator is expressed as a percentage and allows for the comparison of systems. The limitation of the model is the difficulty in obtaining the input data, especially in the calibration of the hydraulic model.

The I_{CC} was applied in a real water-distribution network in the city of João Pessoa, Brazil. As the presented results show, based on the design criteria for calculating the indicator, the I_{CC} reduces from 203.5% in the first year of operation to 70.6% in the 30th year of operation.

When real analyses were incorporated (especially in relation to the demographic growth), the network became inefficient within six years of operation. The results of the I_{CC} contribute to the conditions the water utility technicians reported. They pointed out that the problem of low pressures in the network has been occurring for about 10 years. Consequently, we can see that the results are quite consistent when compared to the actual supply.

At the end of the research, it was concluded that the I_{CC} is adequate to analyze WDNs' hydraulic and energy (in)efficiency. I_{CC} values above 100% indicate that the analyzed network is in sound operational condition regarding its water flow capacity when compared to the standard scenario. Conversely, values less than 100% indicate that the network is hydraulically inefficient because it is consuming more energy with friction losses than was predicted in the baseline scenario. Consequently, in this last case, the supply service's quality may have suffered numerous damages, leading to serious correlated consequences, such as decreased available pressures in part of the supplied area and, consequently, a lack of water in certain points of the network because of piezometric head deficiency.

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